ConF-9009164--2

Oceanic CO_2 Uptake and Future Atmospheric CO_2 Concentrations †

CONF-9009164--2

DE90 017762

Tsung-Hung Peng

Environmental Sciences Division
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6335

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† Research sponsored by Carbon Dioxide Research Program, Atmospheric and Climate Research Division, Office of Health and Environmental Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Publication No. ____. Environmental Sciences Division, Oak Ridge National Laboratory.

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Oceanic CO_2 Uptake and Future Atmospheric CO_2 Concentrations

Tsung-Hung Peng

Abstract: Models of the lateral transport of surface water in the Atlantic, Indian, and Pacific oceans are proposed on the basis of the distribution pattern of bomb-produced ^{14}C in the ocean as observed during the Geochemical Ocean Sections Study program (GEOSECS 1973-1978). The water column inventories of bomb-produced ^{14}C and the input function of the time history of bomb-produced ^{14}C in the atmosphere require that the mean ocean-wide CO_2 exchange flux should be 22.3 $mol \cdot m^{-2} \cdot yr^{-1}$in the Atlantic Ocean, 19.4 $mol \cdot m^{-2} \cdot yr^{-1}$in the Indian Ocean, and 19.2 $mol \cdot m^{-2} \cdot yr^{-1}$in the Pacific Ocean. The global pattern of water column inventories of bomb-produced ^{14}C suggests that an upwelling of bomb-^{14}C-free water takes place in the Antarctic, northern Pacific, and equatorial regions, whereas a downwelling of bomb-^{14}C-rich surface waters occurs in the temperate oceans and northern Atlantic. A global model of the closed ocean-atmosphere system is constructed on the basis of these dynamic flows for the purpose of estimating the oceanic uptake of excess CO_2. To produce a close match between the historical pattern of atmospheric CO_2 predicted by the model and that observed in the Siple ice core and the Mauna Loa record requires that a net release of 82×10^{15} g of carbon from the terrestrial ecosystem be posited for the period 1800-1980, in addition to fossil fuel CO_2 input. The model uses four scenarios of future CO_2 emissions from fossil fuel consumption and tropical deforestation to predict atmospheric CO_2 concentrations. Although the resulting patterns of predicted CO_2 levels are similar to those in the report given by Intergovernmental Panel on Climate Change (IPCC), the uptake of CO_2 from fossil fuel in the lateral transport model is more efficient than that in the general box-diffusion models used by IPCC; that is, all predictions from the model are lower than those given by IPCC.

INTRODUCTION

Since the industrial revolution, the combustion of fossil fuels and deforestation have led to a 26% increase in the atmospheric concentration of CO_2. There is concern that such an increase may change the climate of the globe by increasing the temperature of the Earth's surface, through so-called greenhouse warming. The amount of the temperature increase is related to the atmospheric concentration of greenhouse gases, of which carbon dioxide is a major constituent. To predict greenhouse warming, we need to know the fate of anthropogenic CO_2 after its release into the atmosphere. As a major carbon reservoir, the ocean will eventually absorb most of these human-made CO_2 gases. Although we know that about half of the emitted fossil fuel CO_2 stays in the atmosphere, we do not know well how much of the remainder is taken up by the world's oceans in the short term. Estimates of oceanic uptake of anthropogenic CO_2 and predictions of future atmospheric CO_2 concentrations need to be made by using models of world ocean circulation. Many ocean models have been constructed, and most of which are based on box-diffusion model of Oeschger et al. (1975). A more recent model, the lateral transport model proposed by Broecker et al. (1985), is calibrated from the distribution of bomb-produced ^{14}C in the oceans. Recently, a few three-dimensional ocean general circulation models have been adopted to study the carbon cycle in the ocean: however, they are not yet capable of predicting atmospheric CO_2 levels. In this paper, the lateral transport model of the ocean will be modified to compute the uptake of human-made CO_2 and to predict concentrations of atmospheric CO_2.

LATERAL TRANSPORT MODEL FOR CO_2 UPTAKE

Radiocarbon produced during the nuclear bomb tests in the 1950s and early 1960s is delivered from the atmosphere to the sea surface through gas exchange processes. It is subsequently transported to the deeper oceans through the dynamics of ocean mixing and circulation. By studying the estimated delivery and the measured water column inventory of this bomb-produced ^{14}C, we can calculate the mean CO_2 gas exchange rates for three major ocean basins. Further more, we can place important constraints on the rates at which water is mixed vertically and transported from region to region.

Based on the history of the atmospheric $\Delta^{14}C$ in excess of the prebomb value (as measured directly on CO_2 extracted from the air) and the history of the surface ocean $\Delta^{14}C$ excess, we can calculate the input of bomb ^{14}C if the CO_2 invasion rate for the region is known. Because reliable estimates for the regional variations in CO_2 invasion rates are not available, a single average CO_2 invasion rate for each ocean is assumed (Broecker et al. 1985). By requiring that the total amount of bomb-produced ^{14}C in a given ocean must equal to the net bomb ^{14}C input to that ocean, we can obtain the average CO_2 invasion rate for that ocean. The inventory of bomb-produced ^{14}C for each ocean was derived from measurements of ^{14}C profiles throughout the global oceans during the GEOSECS program (Stuiver and Ostlund 1980, 1983; Ostlund and Stuiver 1980). Net input of bomb ^{14}C to each ocean is calculated by using the required CO_2 invasion rates. Computations balancing the net excess ^{14}C input and the total observed excess ^{14}C inventory for each ocean give invasion rates as follow: 22.3 $mol \cdot m^{-2} \cdot yr^{-1}$for the Atlantic Ocean, 19.4 $mol \cdot m^{-2} \cdot yr^{-1}$for the Indian Ocean, and 19.2 $mol \cdot m^{-2} \cdot yr^{-1}$for the Pacific Ocean.

The global distribution of water column inventories of bomb ^{14}C, as analyzed by Broecker et al. (1985) and summarized in Fig. 1, shows distinctive zonal excesses and deficiencies in ^{14}C inventories with respect to net ^{14}C input in each ocean. The most prominent feature is the presence of excess ^{14}C inventories in the temperate regions and deficient ^{14}C inventories in the equatorial and polar regions. The only exception to the pattern is the high latitude region of the North Atlantic, which shows an excess of ^{14}C inventories. Based on this pattern of distribution, a lateral transport model (Fig. 2) for each ocean was proposed. In the model, water upwells in the equatorial and polar regions.

bringing waters free of bomb-produced-^{14}C from the deep to the surface, whereas water in the temperate regions downwells from the surface to the deep, bringing waters rich in bomb-produced-^{14}C to the deep water column. Because of the lack of other geochemical constraints, the lateral transport of water is assumed to take place in the surface ocean. For the Atlantic Ocean, the surface water is transported mainly from the southern hemisphere toward the northern hemisphere. For the Pacific Ocean, the water upwelled from the equatorial region is mostly transported to the southern hemisphere, and a smaller fraction of it is transported northward.

In addition to the pattern of bomb-^{14}C inventories, the distribution of excess Δ^{14}C (over the prenuclear values) in surface waters also shows a similar zonal pattern, that is, high values in temperate regions and low values in equatorial and polar regions. This distribution pattern provides additional constraints for vertical mixing rates in each latitudinal region. For example, a low value for excess Δ^{14}C in surface waters in the high latitude region of the North Atlantic, coupled with an excess ^{14}C inventory in this region, calls for a high rate of eddy diffusion in the water column. The advective water fluxes and the vertical eddy diffusion rates for each latitudinal region in each ocean are thus determined in order to match the observed distribution of bomb-^{14}C. Table 1 summarizes the model parameters that were derived by Broecker et al. (1985).

To use the lateral transport model for estimating the uptake of human-made CO_2 and predicting atmospheric CO_2 concentrations, we need to have a closed ocean-atmosphere system. Accordingly, the following modifications are made for the lateral transport model (Fig. 2). Beneath the surface mixed layer in each ocean, a diffusive layer is assumed to extend to the depth of 2000 m, and beneath this depth, a well-mixed deep water reservoir is assumed to extend to the bottom of the ocean at 4000 m. Because of the sinking of surface water and the apparent high vertical mixing rate in the high latitudes of the North Atlantic region, the diffusive layer is assumed to extend to the bottom of the ocean. Although the oceans need to be linked to represent a global ocean, the model parameters calibrated in the present fashion will not permit such linkage. However, CO_2 can be transported between oceans through the atmospheric reservoir which is assumed to be well mixed. The revised lateral transport model, as shown in Fig. 2, could be useful in computing CO_2 uptake for a time scale of a few centuries (i.e., shorter than the deep ocean ventilation time of about a thousand years).

The surface temperature, alkalinity, and nutrient concentrations for each region in each ocean are taken from GEOSECS data (Takahashi et al. 1981). Before human-made CO_2 is introduced into this ocean-atmosphere system, a steady-state distribution of ΣCO_2 in each ocean region is computed by fixing the atmospheric CO_2 concentration at 280 ppm. The size of the atmospheric carbon reservoir is taken to be 600 Gt of carbon. The release of anthropogenic CO_2 into the atmosphere is assumed to begin in 1800 A.D. The history of fossil fuel CO_2 release between 1860 and 1949 is taken from Keeling (1973), and that between 1950 and 1990 is taken from Marland (1990). The pre-1860 values are linearly interpolated from zero release in 1800. The computed history of the atmospheric CO_2 content is compared with a standard curve consisting of measured atmospheric CO_2 concentrations from air bubbles in the Siple ice core (Neftel et al. 1985) for the period 1800-1958 and from air samples at the atmospheric monitoring station at Mauna Loa Observatory for the period 1959-1988 (Keeling et al. 1989).

The atmospheric CO_2 (Fig. 3) computed from fossil fuel input only is in general ~14 ppmv lower than the observed values. Apparently other CO_2 sources have to be considered. The most likely extra human-made CO_2 sources are deforestation and oxidation of organic carbon in the soil by agricultural cultivation. The magnitude and time history of these extra sources can be obtained by demanding that the atmospheric CO_2 computed by the model completely match the standard curve. The history of the required extra carbon source is shown in Fig. 4, which indicates that a substantial terrestrial carbon release occurred before 1900, with a maximum release of about 1 Gt per year in 1890. Since 1890, the trend generally declines toward the negative value (i.e., the terrestrial biosphere becomes a sink, notably by 1980). This downward trend was reversed after 1980, and the terrestrial carbon flux reached about 0.85 Gt per year in 1990. The total amount of CO_2 released during the period 1800-1980 is estimated to be about 82 Gt of carbon, an amount which is consistent with the lower end of the range (90-120 Gt) estimated from land use data (Houghton 1989). However, as shown in Fig. 4, the history based on land use data indicates that CO_2 releases have increased steadily since 1800. Furthermore, a drastic increase of carbon flux took place by 1950, and it reached about 2 Gt per year by 1990.

PREDICTION OF THE FUTURE ATMOSPHERIC CO_2

One main objective of studying the ocean dynamics and chemistry is to be able to reliably estimate the role of the ocean in taking up human-made CO_2 in the future under a given scenario of CO_2 emission. The lateral transport model for each ocean is essentially a composite of a number of box-diffusion models with advective flows that are linked in the surface layers. Working from the hypothetical fossil fuel emission cases as proposed by the Intergovernmental Panel on Climate Change (IPCC 1990), the lateral transport model computes the possible future atmospheric CO_2 concentrations. Results of these computations are shown in Fig. 5. A steady-state distribution of carbon in the model ocean is assumed before the human perturbation started in 1800. The transient distributions of anthropogenic CO_2 in the atmosphere and the ocean are computed by using the known fossil fuel productions and the deforestation releases deduced from this model. During the prediction computations for the years after 1990, the deforestation emission is assumed to stay equivalent to 1990 releases, which total 0.85 Gt of carbon per year. In addition to an uncontrolled fossil fuel consumption case, four other hypothetical study cases proposed by IPCC (1990) are adopted for computations. In case (a), fossil fuel emissions continue at constant 1990 levels. In case (b), emissions are reduced to 50% of the 1990 levels and continue at that level. In case (c), emissions are reduced by 2% per year from 1990. In case (d), emissions are allowed to increase 2% per year until 2010 and then are reduced 2% per year after that. Results of prediction indicate that atmospheric CO_2 will remain below 500 ppm for the next century if fossil fuel emissions can be controlled as in these hypothetical cases. However, as in case (e), if the average 20th century increasing trend, with an approximate 1% annual increase in fossil fuel production, is allowed to continue to the next century, a doubling of the preindustrial CO_2 concentration (i.e., about 600 ppm) will occur in 2060, and by 2100 it will reach a level higher than triple the preindustrial CO_2 concentration. These model predictions also indicate that a constant emission level results in an almost linear increase in the atmospheric CO_2 concentration [cases (a) and (b)]. However, in cases of a 2% annual reduction of emissions, the model predicts a stabilizing CO_2 concentration toward the second half of the next century.

The IPCC (1990) has also made predictions of future atmospheric CO_2 with various box-diffusion-types of ocean models using CO_2 emission scenarios (Fig. 6) provided by Working Group III of IPCC. Scenario A is assumed to be an uncontrolled "Business-as-Usual" case, in which the energy supply is coal intensive and the deforestation continues until the tropical forests are depleted. In Scenario B, the energy supply shifts toward lower carbon fuels, notably natural gas, and the deforestation is reversed. In Scenario C the energy supply shifts toward renewable and nuclear energy in the second half of the 21st century. In Scenario D, CO_2 emissions are reduced to 50% of the 1985 levels near the middle of the next century by shifting to renewable and nuclear energy in the first half of the next century. This scenario is designed to stabilize the atmospheric concentration by stringent controls in industrialized countries and moderate growth of emissions in developing countries.

Using these CO_2 emission scenarios and the revised lateral transport model, we can predict concentrations of atmospheric CO_2 for the period 1991-2100. The transient distribution of anthropogenic CO_2 in 1990 is computed in the same way. As shown in Fig. 7, for Scenario A, the atmospheric CO_2 in 2067 is twice the preindustrial concentration. This projection is quite compatible with the IPCC results (e.g., the value for 2060). In fact, the patterns of the atmospheric CO_2 levels predicted by this model are very similar to those given by IPCC for all four scenarios. However, the predicted concentrations are lower than the IPCC results because of the more efficient CO_2 uptake in the lateral transport models. In Scenario D, for example, the lateral transport model gives a stabilized atmospheric CO_2 of 410 ppm by the middle of the next century, whereas IPCC gives 450 ppm. However, concentrations for Scenarios B and C in the model never reach 600 ppm before 2100, levels which are consistent with IPCC results.

CONCLUSIONS

The Broecker et al. (1985) lateral transport model of the world ocean have been revised to calculate the uptake of anthropogenic CO_2 and to predict atmospheric CO_2 concentrations for the next century. The results of this model show a more efficient uptake of CO_2 than those of box-diffusion models used by IPCC. Although the lateral transport model is calibrated with the distribution of bomb-produced ^{14}C, the carbon chemistry and nutrient distribution have not been calibrated with the observed data. To make predictions of atmospheric CO_2 concentrations more realistic, nutrient distribution, and hence the biological carbon fluxes, needs to be taken into consideration. In addition, because the global ocean is a single body of water, with the regional major oceans connected by the Antarctic ocean, the individual lateral transport models for each ocean need to be linked into a single global model. To do so, the distribution of bomb-produced ^{14}C will have to be analyzed again, especially in the Antarctic regions. Calibration of this new model will require substantially more data about ^{14}C and nutrients in the Antarctic Ocean than are currently available from the GEOSECS program in 1973-1978.

ACKNOWLEDGEMENT

I thank W. R. Emanuel and A. W. King for reviewing the manuscript. Research sponsored by the Carbon Dioxide Research Program, Atmospheric and Climate Research Division, Office of Health and Environmental Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Publication No. 0000, Environmental Sciences Division, Oak Ridge National Laboratory.

Table 1. Summary of model parameters[a]

Latitude belt	Area (10^{12}m^2)	W (m/year)	Flux (sverdrups)	K (cm^2/s)	Z (m)
			Atlantic Ocean		
80°N-40°N	18.6	-8.5	-5	9.9	710
40°N-20°N	15.8	-30.0	-15	0.5	470
20°N-20°S	26.7	+21.2	+18	1.0	190
20°S-45°S	18.4	-22.3	-13	1.0	400
45°S-80°S	15.1	+31.2	+15	3.0	270
			Indian Ocean		
25°N-15°S	27.0	+15.2	+13	1.0	215
15°S-45°S	29.8	-20.1	-19	1.0	510
45°S-70°S	20.7	+9.1	+6	3.0	410
			Pacific Ocean		
65°N-40°N	15.1	+10.4	+5	1.5	260
40°N-15°N	35.0	-10.8	-12	1.0	365
15°N-10°S	50.0	+16.4	+26	1.0	255
10°S-55°S	63.0	-12.5	-25	2.0	410
55°S-80°S	13.8	+13.7	+6	3.0	335

[a] W = Mean advective flow rate (minus represents downwelling); K = Vertical diffusivity; and Z = Mean penetration depth of bomb-produced ^{14}C

Figure Captions

Fig. 1. Bomb testing ^{14}C inventories as measured during the GEOSECS, NORPAX, and TTO programs (as summarized by Broecker et al. 1985). The dashed lines show the amount expected at the time of the GEOSECS program under the assumption that there was no lateral transport from one zone of each ocean to another.

Fig. 2. Modified lateral transport models for the Atlantic, Indian, and Pacific oceans. The well-mixed atmospheric box linked these oceans during the CO_2 uptake calculations. The magnitude of the advective flows and the vertical diffusivity for each water column are summarized in Table 1.

Fig. 3. Model-derived atmospheric CO_2 concentration (dashed curve) when fossil fuel combustion is assumed to be the sole source of perturbation. The solid curve represents observed concentrations of atmospheric CO_2 from the Siple ice core and the Mauna Loa atmospheric record.

Fig. 4. Extra CO_2 sources (solid curve) needed to match the ocean-model-derived atmospheric CO_2 curve with the observed one. The dashed curve represents the level of CO_2 emissions that result from deforestation, as derived from land use data (Houghton 1989; values before 1855 are linearly interpolated on the basis of zero emissions in 1770).

Fig. 5. Atmospheric CO_2 concentrations predicted by the lateral transport model using five hypothetical fossil fuel emissions: (a) constant at the 1990 level, (b) constant at 50% of the 1990 level, (c) reduced by 2% per year from 1990, (d) growing by 2% per year from 1990 until 2010 and then reduced by 2% per year thereafter, and (e) current trend of the uncontrolled growth into the next century.

Fig. 6. CO_2 emission scenarios and predicted CO_2 concentrations published by the Intergovernmental Panel on Climate Change. Details of each scenario are given in the text.

Fig. 7. Atmospheric CO_2 concentrations predicted by the lateral transport model using four CO_2 emission scenarios proposed by Intergovernmental Panel on Climate Change. The CO_2 concentrations in this figure for year 2100 are 784, 549, 478, and 411 ppmv for scenarios A, B, C, and D, respectively.

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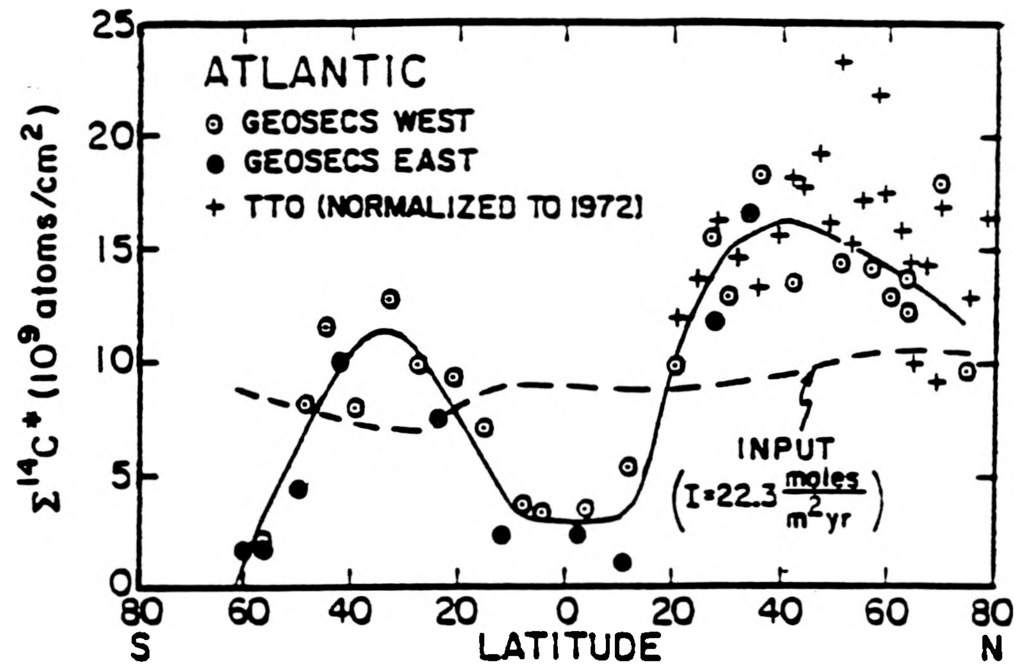
ATLANTIC
GEOSECS WEST
GEOSECS EAST
TTO (NORMALIZED TO 1972)
INPUT
(I=22.3 moles/m²yr)
Σ14C* (10⁹ atoms/cm²)
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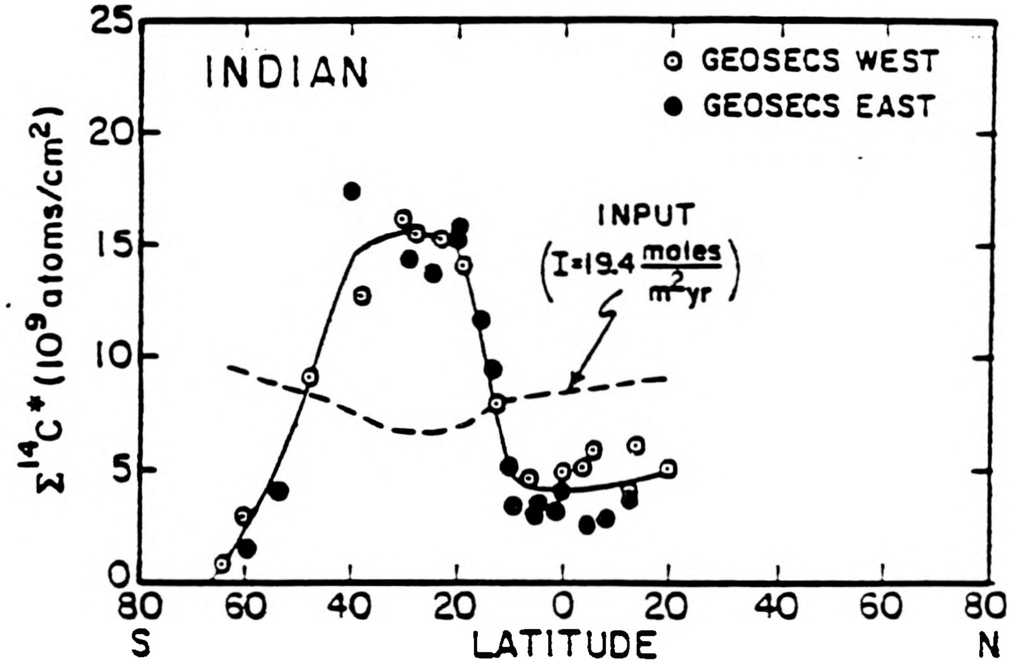
5
10
15
20
25
80 S
60
40
20
0
20
40
60
80 N
LATITUDE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GEOSECS WEST
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INPUT
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Σ14C* (10⁹ atoms/cm²)
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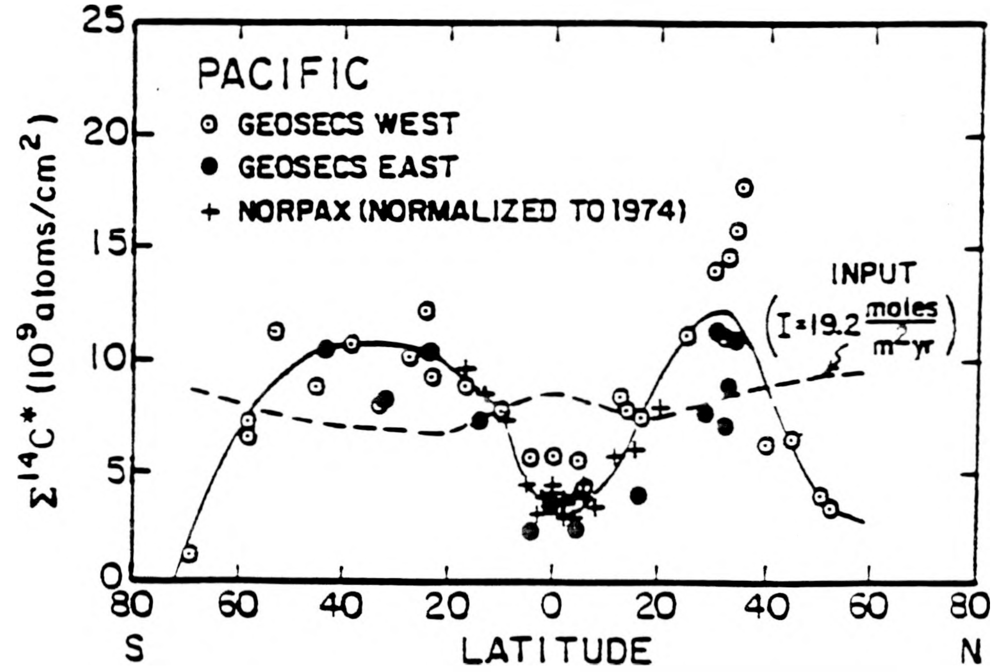
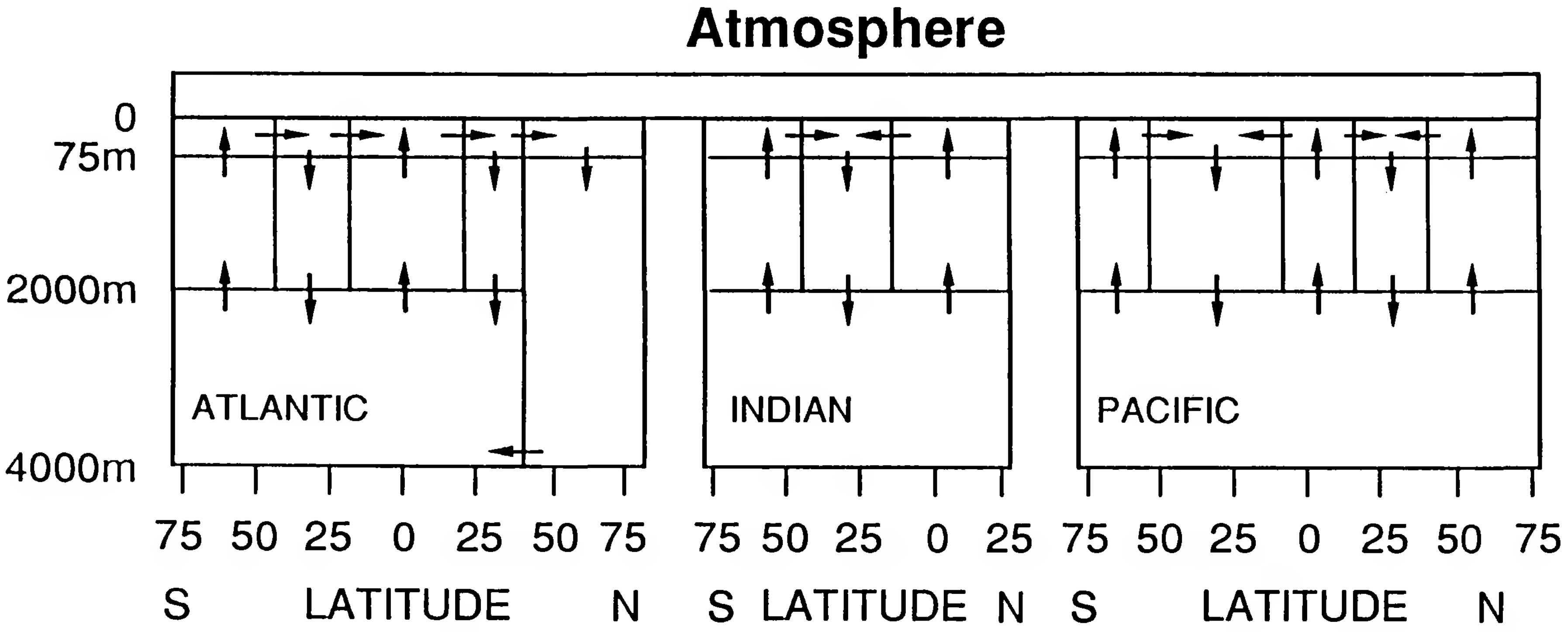
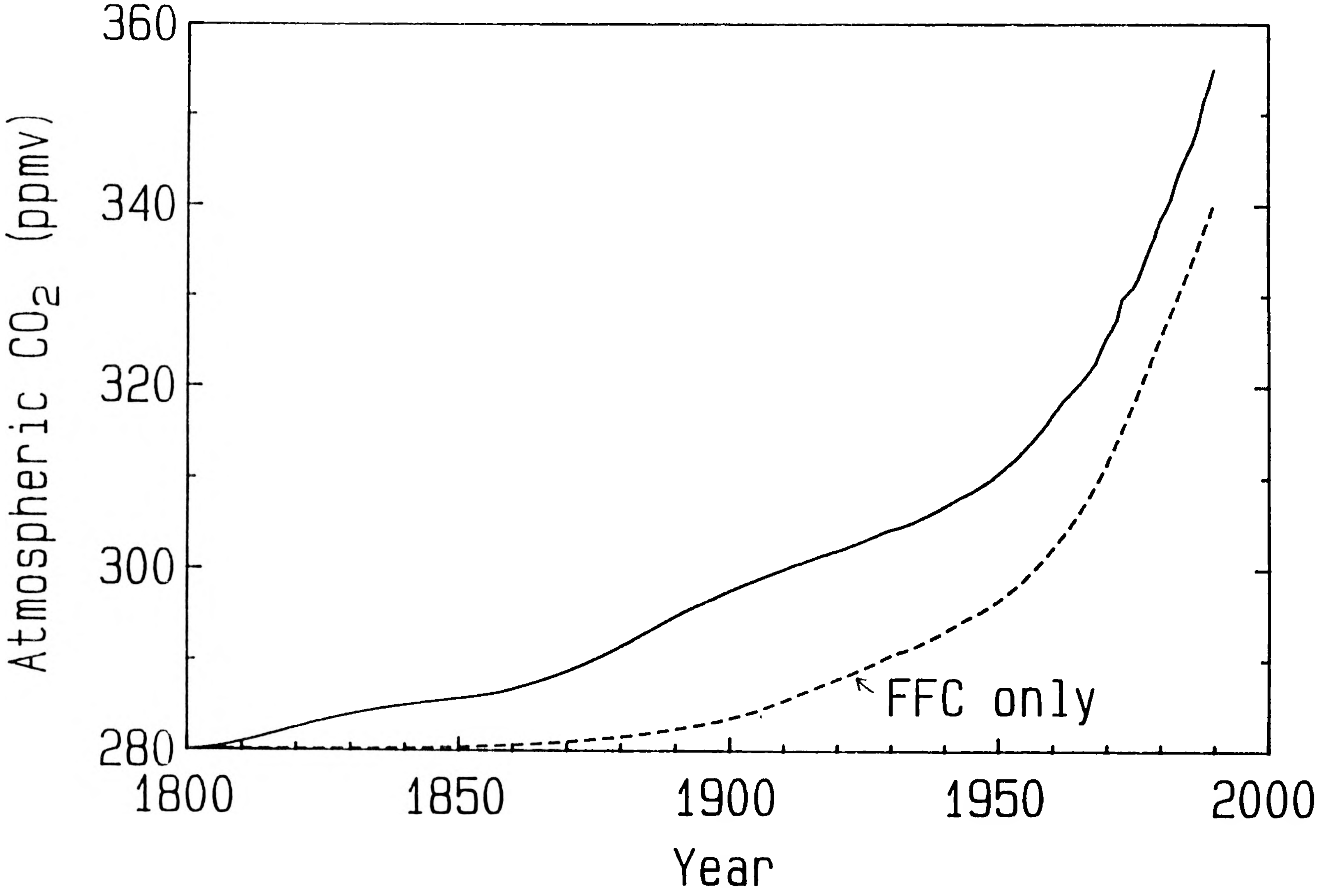
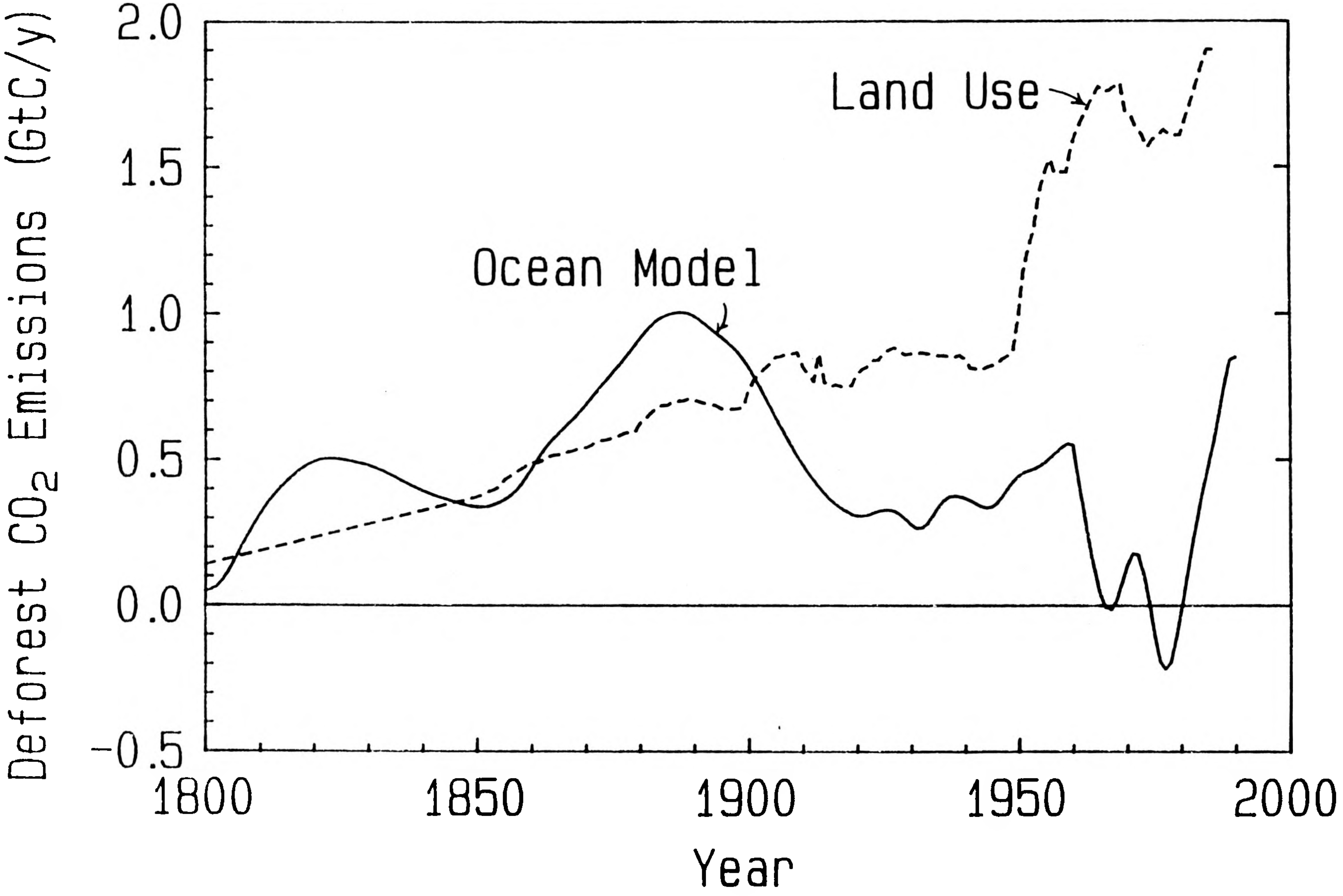
10
15
20
25
80 S
60
40
20
0
20
40
60
80 N
LATITUDE


PACIFIC
GEOSECS WEST
GEOSECS EAST
NORPAX (NORMALIZED TO 1974)
INPUT
(I=19.2 moles/m²yr)
Σ14C* (10⁹ atoms/cm²)
0
5
10
15
20
25
80 S
60
40
20
0
20
40
60
80 N
LATITUDE

ORNL-DWG 90M-13416




360
340
320
300
280
Atmospheric CO_2 (ppmv)
1800
1850
1900
1950
2000
Year
FFC only


Land Use
Ocean Model
Deforest CO_2 Emissions (GtC/y)
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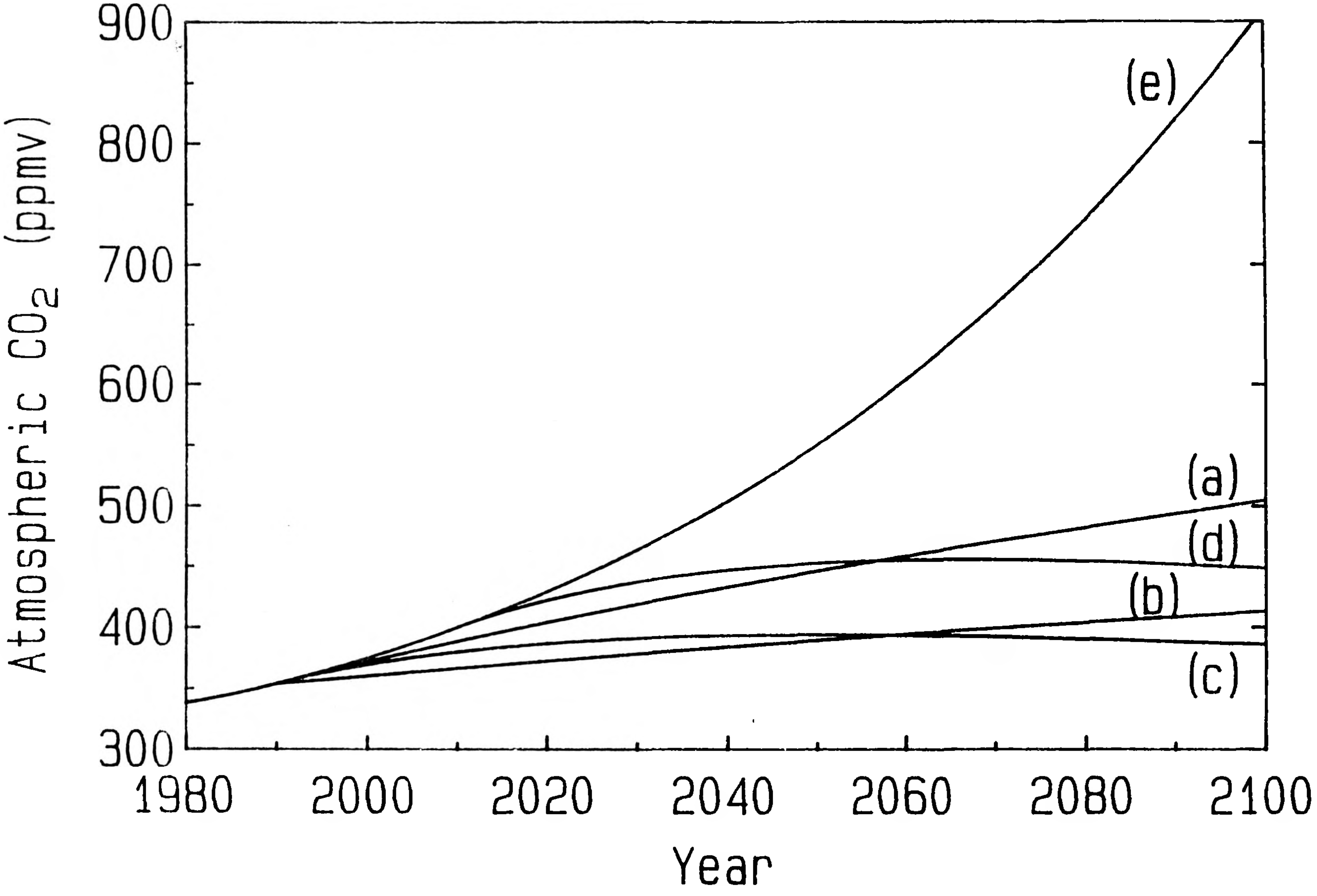
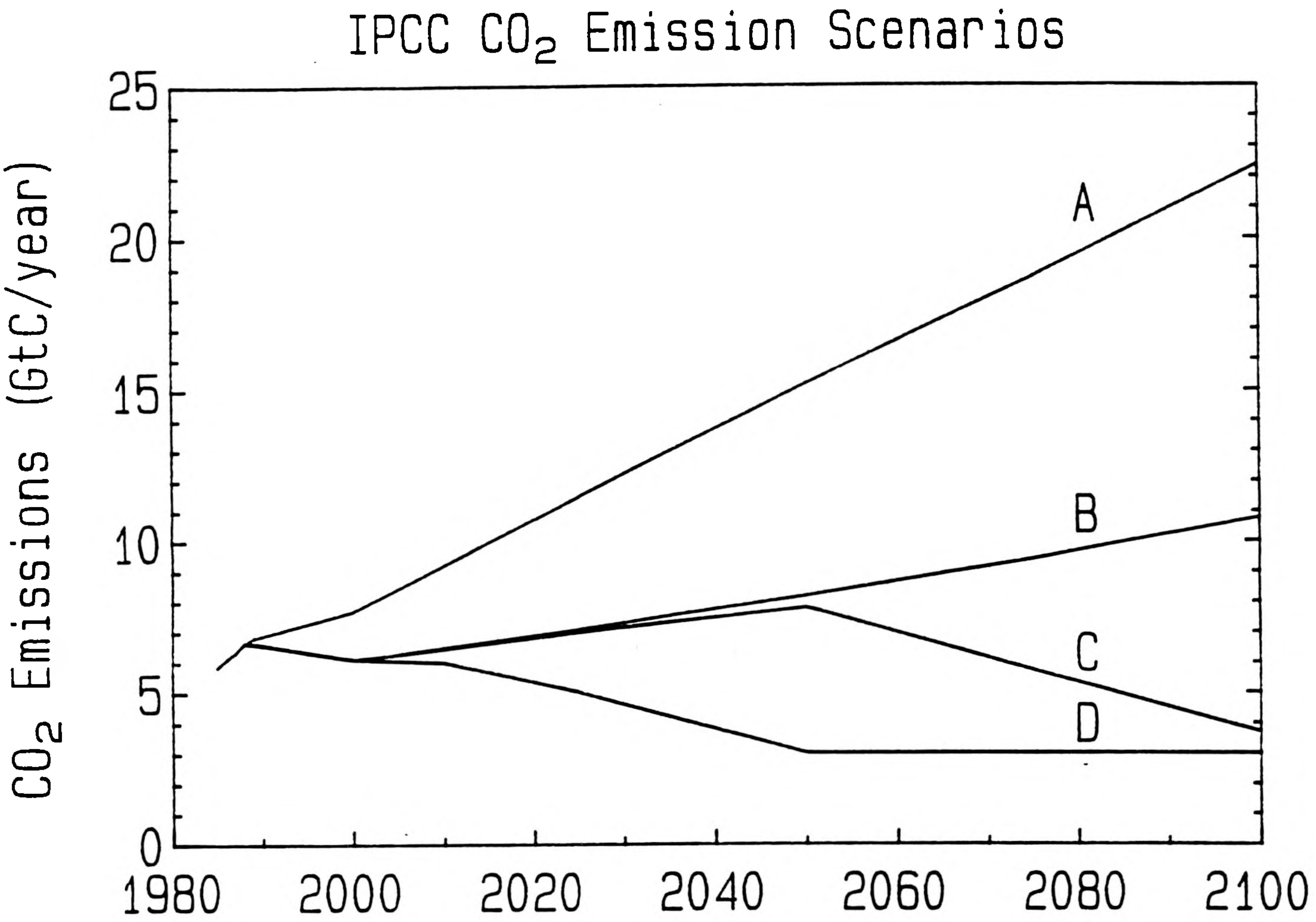
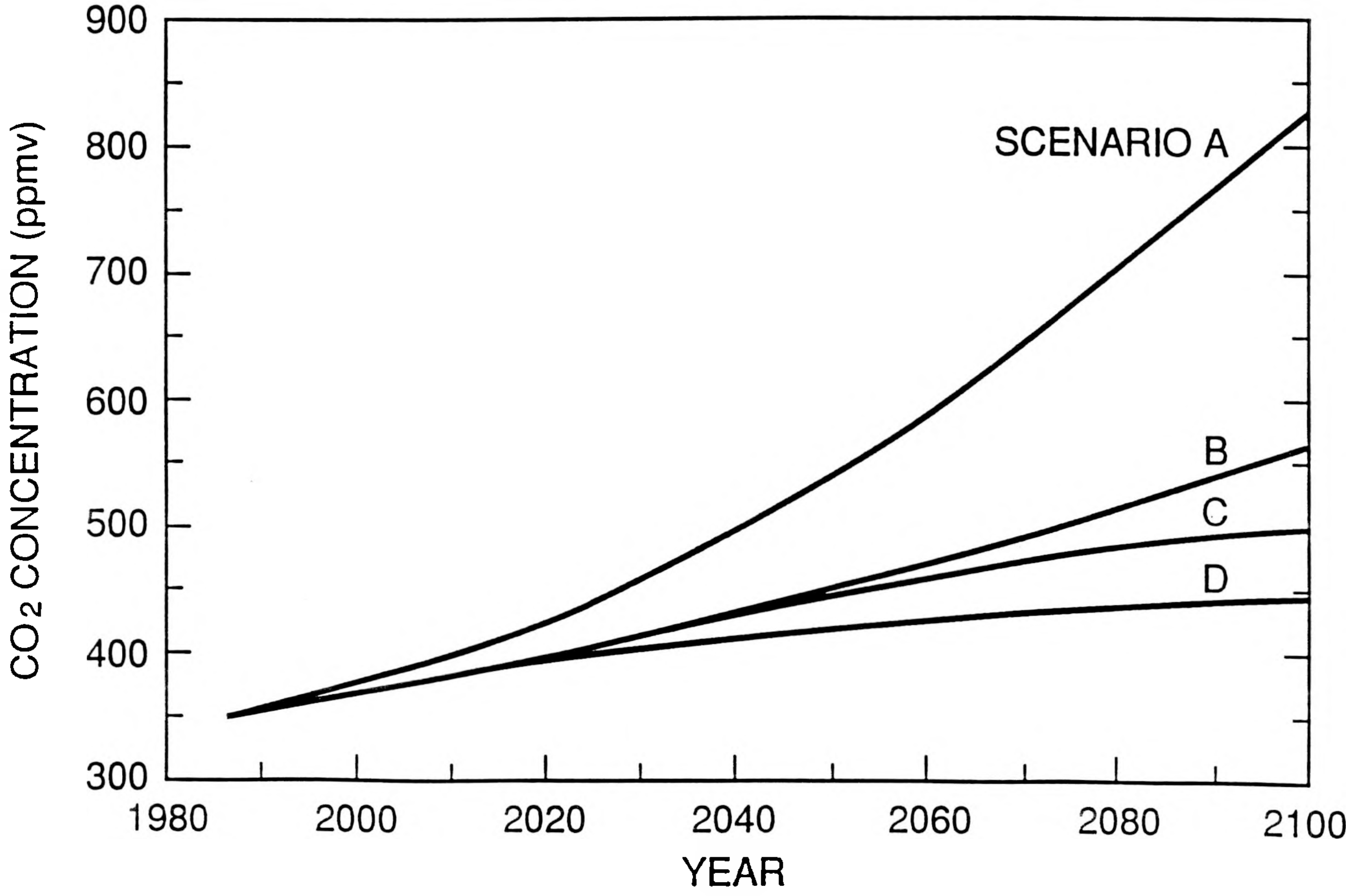
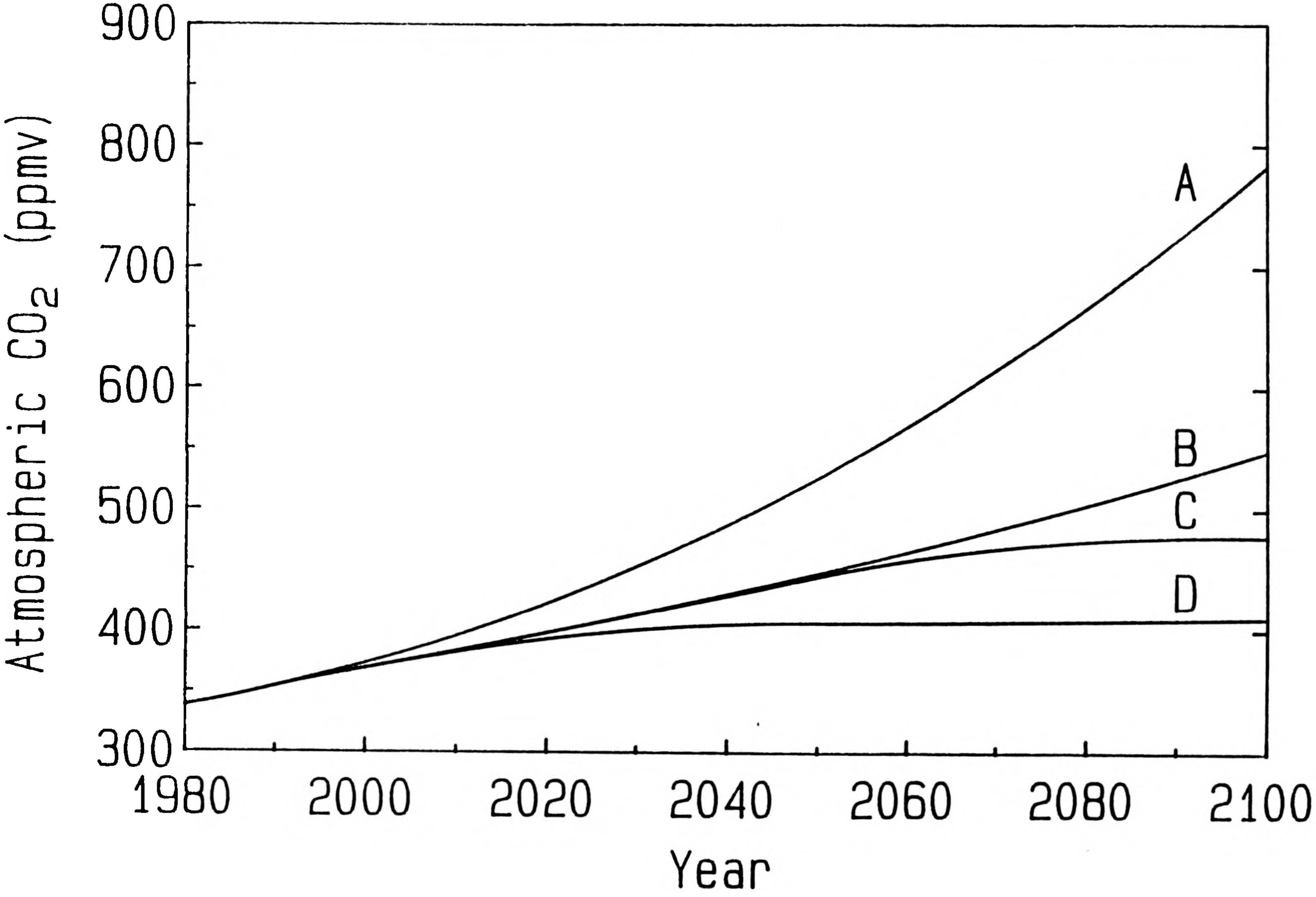
1.5
1.0
0.5
0.0
−0.5
1800
1850
1900
1950
2000
Year


900
800
700
600
500
400
300
Atmospheric CO_2 (ppmv)
1980
2000
2020
2040
2060
2080
2100
Year
(e)
(a)
(d)
(b)
(c)


IPCC CO_2 Emission Scenarios
CO_2 Emissions (GtC/year)
25
20
15
10
5
0
1980
2000
2020
2040
2060
2080
2100
A
B
C
D


CO_2 CONCENTRATION (ppmv)
900
800
700
600
500
400
300
1980
2000
2020
2040
2060
2080
2100
YEAR
SCENARIO A
B
C
D


900
800
700
600
500
400
300
Atmospheric CO_2 (ppmv)
1980
2000
2020
2040
2060
2080
2100
Year
A
B
C
D